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A PRELIMINARY STUDY ON THE EFFECTS OF SUSPENDED SEDIMENT ON THE SURVIVAL OF EARLY LIFE STAGES OF THE MAHIMAHI, *CORYPHAENA HIPPURUS*

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NOT FOR PUBLICATION

ADMINISTRATIVE REPORT H-86-18

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A PRELIMINARY STUDY ON THE EFFECTS OF SUSPENDED SEDIMENT ON THE SURVIVAL OF EARLY LIFE STAGES OF THE MAHIMAHI, *CORYPHAENA HIPPURUS*

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INTRODUCTION

Ocean mining, large-scale coastal construction projects, and ocean dumping can increase the suspended load of sediments over large areas of ocean. An interagency planning group recently emphasized the need for more research on the potential environmental impacts of turbidity plumes resulting from these types of activities (Boehlert et al. 1985). Interest in this subject extends beyond the concerns of environmental and fisheries management. The question is relevant to basic aquatic ecology. Organisms inhabiting estuaries, rivers, and embayments are often subjected to highly turbid conditions, but organisms of the tropical pelagic realm live in water that is very low in suspended matter. Information on the ability of pelagic fish larvae to tolerate sediment loading would contribute to our understanding of this ecological parameter. The problem is physically multidimensional in regard to size distribution of particles, total load, and chemical composition. The possible biological impacts are much more diverse and involve a multitude of species, different life stages, and interactions.

The Programmatic Environmental Impact Statement (National Oceanographic and Atmospheric Agency 1981) that was conducted in response to the Deep Seabed Hard Minerals Resources Act and the National Environmental Policy Act identified a need for more information on the possible effects of suspended solids on fish larvae. Studies on the environmental impact of mining operations on phytoplankton, macrozooplankton, and adult fish have been conducted (Ozturgut et al. 1980; Chan and Anderson 1981; Hirota 1981; Lavelle and Ozturgut 1981; Lavelle et al. 1982; Matsumoto 1984). Although these studies were directed at effects of manganese nodule mining, much of the background material and many of the conclusions are relevant to manganese crust mining as well as other operations that increase sediment loading in the pelagic environment. The previous studies include data on dispersal of surface plumes and effects of suspended particulate material on phytoplankton and zooplankton in the tropical pelagic realm. Laboratory experiments with tunas exposed to levels of suspended solids encountered near mining operations have also been conducted (Barry 1978). Results suggest that adult tunas would not be affected by discharge from mining operations. The impact of particulates on the survival and growth of fish larvae has not been addressed adequately as emphasized by Hirota (1981) and Matsumoto (1984). Larvae are very delicate and lack the mobility to avoid sediment plumes. The lack of data on larvae of pelagic species is due to the extreme difficulty involved in their laboratory culture. The species chosen for this study was the dolphin, Coryphaena hippurus, known as the mahimahi in Hawaii.

MATERIALS AND METHODS

Experiments were conducted at the Kewalo Research Facility of the Southwest Fisheries Center Honolulu Laboratory, where this species has been cultured through its entire life cycle.

Production of Eggs and Larvae Used in the Experiments

Adult mahimahi brood stock was maintained at the Kewalo Research Facility in large circular tanks of 7.2 m diameter and 1 m depth supplied with a continuous flow of aerated seawater providing a turnover time of <1 h. The fish were maintained in temperatures of 23° to 25°C and fed a diet of squid, fish, and vitamins. The brood stock typically spawned every other day.

Mahimahi eggs are spherical (1.5 to 1.7 mm diameter) and buoyant. They were normally collected within an hour of spawning with a fine mesh dip net as they floated near the surface. Eggs were transferred into cylindrical 150 L laboratory aquaria that contained mildly aerated filtered seawater. Under these conditions the eggs will hatch within 50 to 60 h after spawning. Newly hatched mahimahi larvae measure approximately 4.5 to 5.5 mm standard length. Marine microalgae, *Tetraselmis* sp. and *Isochrysis* sp., were added to maintain water quality. At 25°-26°C the yolk is absorbed by day 2 posthatch, so the tank was inoculated at that time with planktonic rotifer, *Brachionus* sp., at a concentration of approximately 2/ml. This concentration of food was maintained throughout the entire experiment.

Selection of Sediment Types and Sedimentation Levels to be Tested

A typical marine mining operation (reviewed in Matsumoto 1984) would have a discharge concentration on the order of 6 mg/L of suspended solids. The materials mix or sink rapidly in the water column, and within 15 min are diluted to a concentration of <1 mg/L. After 24 h the discharge plume dissipates to a concentration of <0.05 mg/L.

Typical ocean dumping operations of dredge spoils off Oahu caused a measurable increase in turbidity of the receiving waters for a relatively short period of 2 to 5 h (Environmental Protection Agency 1980), although a visually noticeable plume can sometimes persist for much longer (J. J. Naughton[1]). The highest concentration observed in the water immediately after dumping was 60 mg/L (Chave and Miller 1977). This was rapidly dissipated to a concentration of 1 mg/L or less.

Suspended solid concentration in the surface waters immediately downstream of the Barbers Point channel dredging operation (February 1983 to October 1983) was approximately 20 mg/L or less (Harrison 1986). Again, this value rapidly diminished to levels of 1 mg/L or less as the plume dispersed offshore. The most turbid inshore waters found in Hawaii are in disturbed areas that had been previously dredged and filled (e.g., Honolulu Harbor or Keehi Lagoon). These "worst cases" typically contain a total

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[1]J. J. Naughton, Fishery Biologist, Western Pacific Program Office, Honolulu, HI 96822-2396, date, pers. commun.).

suspended solid load of only about 6 mg/L (Chapman 1979) and are diluted to levels well below 1 mg/L as they are carried offshore by currents.

In sum, the highest concentration of suspended sediment resulting from ocean mining, ocean dumping, or coastal construction is highly localized with a maximum concentration of from 5 to 50 mg/L. In general, larger areas of ocean are subjected to plumes with a suspended load of 1 mg/L or less of suspended solids. Realistic exposure times of larvae to concentrations of suspended solids of 5 to 50 to mg/L is probably <15 min and prolonged (1 to 2 h) exposure to suspended solid levels of 1 mg/L or less.

Our initial tests were designed to exceed this anticipated "typical environmental loading level" of approximately 1 mg/L by several orders of magnitude. Loading levels were set at 0, 500, 1,000, 2,000, 4,000, and 8,000 mg/L. These are the same concentrations used by Boehlert et al. (1983) and Boehlert and Morgan (1985) in studies of the effect of suspended solids on the eggs and larvae of the Pacific herring. Subsequent tests would be conducted at lower concentrations if indicated by preliminary results.

Incubation Chambers

One of the technical problems encountered in this study was the design of an apparatus that could keep the sediment suspended in the water while providing low-turbulence conditions suitable for the maintenance of these organisms. We thus chose to use the apparatus previously used in a series of experiments on the effects of turbidity on feeding abilities of larvae of the Pacific herring (Boehlert and Morgan 1985). This apparatus consists of small (1 L) incubation chambers that are gently flushed with recirculating seawater. The initial two experiments that evaluated effects of sediment on egg development and hatching were conducted in this apparatus. We did not obtain any evidence that the chambers influenced egg development or hatching rate as will be shown in the results section. The containers did, however, inflict high mortality on the larvae of _C. hippurus_ after hatching. This necessitated use of larger containers for the larva tests. A series of four experiments was designed to compare 24-h larval mortality in the Boehlert and Morgan (1985) apparatus with mortality in large volume (30 L) chambers previously used at the Kewalo Research Facility to culture the mahimahi larvae. All larvae died within 24 h in the smaller chambers regardless of flow rate, level of turbulence, or age of larvae. Very low rates of 24 h mortality occurred in the 30-L control containers. Larvae of _C. hippurus_ seem to be unable to withstand mechanical damage inflicted by bumping into the walls of small containers, so the larger containers were used in the tests.

Large amounts of sediment could be suspended in this system by placing an airstone in the vertex of the concave bottom. The containers used were 40 cm in diameter with vertical walls of 25 cm that sloped to a maximum depth of 30 cm in the center of the container. An air flow of 500 cc/min created enough turbulence to keep the clay and silt in suspension, yet not damage the larvae. Little or no sediment was able to adhere to the steep container walls. The turbulent convection current from the airstone at the lowest point on the concave bottom was sufficient to prevent settling of fine suspended material. Temperature was maintained at 26° ± 1°C by holding the containers in a thermally regulated water bath. All experiments were conducted at the same level of controlled illumination (approximately 50 fc from fluorescent 40-W tubes). An artificial day-night cycle of 13 h on and 11 h off was maintained throughout the experiment.

Sediment

Several types of sediment were tested. We selected material representative of that which might impact the pelagic environment of the larval mahimahi. These include sediments typical of the type produced by coastal construction, dredging for harbor construction and maintenance, ocean mining, and ocean dumping. Most of these materials are chemically inert minerals. Potential toxins and high organic biochemical oxygen demand could be a problem with some sediments such as harbor dredgings. Grain size distribution of all materials used in the experiments was determined with a Coulter Counter using the method of Hirota (1981). Results of the analysis are shown in Table 1. A description of these sediments follows:

Kaolin

Hyrated aluminum silicate is one of the primary end weathering products of volcanic rock and ferromagnesian minerals. We used a pure form of this silicate clay (Sigma Chemical Company K-7375[2]) which consists of particles in the 0.1 to 4 m size range.

Bentonite (Montmorillonite)

This aluminum-magnesium silicate clay is a primary weathering product of volcanic rock and ferromagnesian minerals. In the weathering series it is a precursor of kaolin. We used a pure form of this clay (Sigma Chemical Company B-3378). This clay has a high swell to shrink ratio and is often used to seal water reservoirs against seepage.

Pelagic Carbonate Clay

Calcarious ooze dredged from near Gardiner Pinnacles was used in these experiments. It is typical of material that might be brought to the surface of the ocean during ocean mining operations at shallower depths.

Pelagic Red Clay

Red clay dredged from near Gardiner Pinnacles was used as a typical sediment from the deeper ocean that is commonly associated with manganese nodules.

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[2] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

Table 1.--Results of Coulter Counter analysis of size distribution for material used in these experiments. Legend of abbreviations: B = bentonite, BP = dredgings from Barbers Point Deep Draft Harbor, C = calcareous ooze, K = kaolinite, MC = manganese crust, PH = dredgings from Pearl Harbor, R = red clay.

Sediment type	Lower diameter in microns													
	1.3	1.6	2.0	2.5	3.2	4.0	5.0	6.3	8.0	10.1	12.7	16.0	20.2	25.4
B	16.9	16.6	15.2	13.6	10.7	8.7	4.8	4.1	4.0	3.0	2.2	0.1	0.6	0.1
BP	6.2	9.0	13.3	15.7	13.3	11.6	9.1	6.8	5.0	3.5	4.3	0.2	2.1	0.0
C	1.5	2.0	3.9	7.0	10.9	15.7	15.7	14.7	9.0	7.8	5.8	3.3	1.4	1.3
K	61.1	27.3	8.5	2.5	0.7	0.3	0.1	0.2	0.7	1.3	1.6	0.0	0.0	0.0
MC	2.2	2.9	7.1	10.0	10.3	10.0	8.6	9.2	9.3	8.7	8.3	6.4	4.6	2.8
PH	2.5	3.4	4.8	6.8	8.0	9.2	10.0	10.6	10.6	9.0	6.8	7.5	7.6	3.1
R	0.2	0.0	0.3	0.5	0.7	1.0	2.5	6.0	13.4	23.1	24.8	15.2	7.3	5.1

Pulverized Manganese Crust

Samples of manganese crust from the Exclusive Economic Zone in the Northwestern Hawaiian Islands were pulverized into fine sediment in a mortar and pestle and passed through a 100- m mesh sieve. The pulverized material represents one type of fine sediment that might result from an ocean mining operation.

Barbers Point (Oahu) Deep Draft Harbor Carbonate Mud Dredge Spoils

Mud was dredged from the bottom of the inner Barbers Point Deep Draft Harbor near the completion of dredging operations in July 1985. This harbor was dredged out of an emergent reef platform, and the dredge spoils consist almost entirely of carbonate materials. Organic matter was extremely low or absent in the spoils as indicated by lack of anoxia, even when the sediments were stored in a covered pail for many weeks. The material is a carbonate mud typical of that produced by dredging or erosion of coral reefs. The material was further fractionated by resuspension in water and the coarse fraction allowed to settle out within the first 10 min. The suspended fine material was decanted into another container and allowed to fully settle.

Dredgings from Pearl Harbor, Oahu

Dredge spoils from harbors are commonly dumped at sea. Extensive sediment plumes result, with unknown consequences to the surrounding pelagic ecosystem (J. Naughton, fn. 1). Material used in this study was dredged from the bottom of the main ship channel in Pearl Harbor, Hawaii at a location adjacent to the main shipyard. This type of material differs from the others in that it has a higher organic content. Harbor dredgings could contain toxic substances as well, such as heavy metals, hydrocarbons, and hydrogen sulfide.

Experimental Procedure

The proper amounts of sediment were weighed and set aside. The amount of moist sediment to be added to each treatment was calculated using measured wet to dry weight ratio for each sediment type. The experimental aquaria were filled with 29 L of filtered seawater and allowed to equilibrate in the constant temperature water bath while being aerated at a rate of 500 cc/min. Two liters of water were retained for later use in homogenizing sediment with a food blender and for rinsing the stock sediment from the blender into the experimental aquaria. Larval fish were then gently added to each container since they are very easily damaged by handling. Such damage was minimized by using a bowl to carefully scoop individual larvae from the rearing container and gently placing them into the experimental chamber. For feeding larvae, the aquaria were stocked with rotifers at approximately 2/ml. Sediment was then mixed into a slurry with a portion of the remaining liter of seawater in a commercial blender and slowly added to the experimental aquaria. The last portion of seawater was used to rinse the blender into the experimental aquarium.

Effects of Suspended Solids on Egg Survival, Development, and Hatching Rate

Experiment E-1 was designed to test the effect of sediment load on egg development. Sediment type was Barbers Point Deep Draft dredge tailings. The experiment was conducted in the chambers described by Boehlert and Morgan (1985) using four replicates each at six treatment levels (0, 500, 1,000, 2,000, 4,000, and 8,000 mg/L). Twenty fertile eggs (approximately 8 h postfertilization) were added to each of the 24 chambers. Duration of the experiment was 24 h, after which time the eggs were examined with a microscope for mortality or retarded development.

Experiment E-2 was run in the same manner as experiment E-1, except that fine kaolin was used as suspended solid, because the carbonate dredge tailings used in experiment E-1 did not produce egg mortality even at the extremely heavy loadings of 8,000 mg/L. Fine kaolin is very "sticky" and can adhere to surfaces.

Experiment E-3 was a continuation of experiment E-2, but extended exposure time from the original 24 h to a full 4 d of exposure to allow enough time for all eggs to hatch. We lengthened exposure time because of the lack of egg mortality in 24 h, even at the highest concentration of 8,000 mg/L of kaolin.

Effects of Suspended Solids on Larvae Mortality and Feeding

This series of experiments was designed to identify the most sensitive larval stage and also to identify possible differences in the impact of different sediment types. All of the experiments on larvae were conducted in the same manner as described above but used the larger 30-L containers. The experiments differed from each other only in type of sediment, age of larvae, and exposure time. The differences between the various experiments are noted in Table 3. Each experiment involved the use of six treatments run simultaneously and proceeded in a logical order, with each being based on results of the previous one. These experiments are extremely time consuming, especially those involving larvae that were of feeding age. Also, the necessity of using very large containers to insure larval survival precluded the use of multiple replicates. Therefore, it was necessary to run an experiment, review the results, and then plan the next logical one. Repetition of this procedure was continued until we had developed confidence in the observed trends.

One important point must be emphasized here. Long-term experience in the culturing of this species at this laboratory suggests that one can only compare results between treatments in a controlled experiment where all larvae are taken from the same batch of eggs and where all larvae used in the experiment have been reared in the same container. Different batches of larvae can be more or less sensitive depending on many environmental, genetic, and nutritional factors that cannot be adequately predicted or controlled between batches. In work with such delicate fish larvae, mortality can be high even within the control treatment. Because the

Table 2.--Summary of egg mortality and hatching data for eggs of Coryphaena hippurus. Legend of abbreviations: B = bentonite, BP = dredgings from Barbers Point Deep Draft Harbor, C = calcareous ooze, K = kaolinite, MC = manganese crust, PH = dredgings from Pearl Harbor, R = red clay.

Exp. No.	Date	Egg stocking density (No./L)	Sediment Type	Sediment Concentration (mg/L)	Exposure time (h)	Egg mortality N	Egg mortality (%)	Egg development (%)	Egg hatch (%)
E-1	8/27/85	1	BP	0	24	20	0	Normal	--
				500	24	20	0	Normal	--
				1,000	24	20	0	Normal	--
				2,000	24	20	0	Normal	--
				4,000	24	20	0	Normal	--
				8,000	24	20	0	Normal	--
E-2	8/29/85	20	K	0	24	80	0	Normal	--
				500	24	80	0	Normal	--
				1,000	24	80	0	Normal	--
				2,000	24	80	0	Normal	--
				4,000	24	80	0	Normal	--
				8,000	24	80	0	Normal	--
E-3	8/31/81	20	K	0	96	80	5	Normal	95
				500	96	80	0	Normal	100
				1,000	96	80	7	Normal	93
				2,000	96	80	0	Normal	100
				4,000	96	80	2	Normal	98
				8,000	96	80	10	Normal	90

Table 3.--Summary of mortality and feeding data for larvae of *Coryphaena hippurus*. Legend of abbreviations: B = bentonite, BP = dredgings from Barbers Point Deep Draft Harbor, C = calcareous ooze, K = kaolinite, MC = manganese crust, PH = dredgings from Pearl Harbor, R = red clay.

Exp. No.	Date	Larva age (d)	Larva stocking density (No./L)	Sediment		Rotifer stocking density (No./L)	Time (h)	Larva mortality (%)	Feeding[1]	
				Type	Concentration (mg/L)				Rotifers	Cysts
L-1	11/6/85	0	1.7	K	0	0	2	14	--	
					500	0	2	16	--	
					1,000	0	2	22	--	
					2,000	0	2	10	--	
					4,000	0	2	16	--	
					8,000	0	2	28	--	
L-2	11/10/85	3	1.7	K	0	0	2	42	--	
					500	0	2	--	--	
					1,000	0	2	20	--	
					2,000	0	2	12	--	
					4,000	0	2	30	--	
					8,000	0	2	50	--	
L-3	11/13/85	0	1.7	B	0	0	2	0	--	
					500	0	2	30	--	
					1,000	0	2	58	--	
					2,000	0	2	30	--	
					4,000	0	2	26	--	
					8,000	0	2	62	--	
L-4	11/14/85	7	1.7	K	0	5	2	0	--	
					500	5	2	4	--	
					1,000	5	2	4	--	
					2,000	5	2	0	--	
					4,000	5	2	12	--	
					8,000	5	2	12	--	
L-5	11/16/85	3	1.7	B	0	0	2	0	--	
					500	0	2	0	--	
					1,000	0	2	0	--	
					2,000	0	2	2	--	
					4,000	0	2	4	--	
					8,000	0	2	12	--	
L-6	1/7/86	5	1.7	K	0	5	2	6	16.3	3.1
					500	5	2	30	21.1	3.9
					1,000	5	2	26	2.0	1.6
					2,000	5	2	26	0.9	0.9
					4,000	5	2	52	1.4	1.7
					8,000	5	2	100	--	--
L-7	1/15/86	3	1.0	K	0	5	24	20	21.0	2.6
					500	5	24	17	9.1	1.4
					1,000	5	24	6	3.2	1.6
					2,000	5	24	17	0.8	0.4
					4,000	5	24	14	2.6	2.2
					8,000	5	24	17	0.6	1.0
L-8	1/24/86	4	1.7	None	0	5	24	26	--	--
				K	1,000	5	24	68	--	--
				C	1,000	5	24	54	--	--
				RC	1,000	5	24	32	--	--
				B	1,000	5	24	100	--	--
				MC	1,000	5	24	46	--	--
L-9	2/4/86	7	1.7	None	0	5	2	0	--	--
				RC	500	5	2	0	--	--
				RC	1,000	5	2	0	--	--
				MC	500	5	2	0	--	--
				MC	1,000	5	2	4	--	--
				K	500	5	2	0	--	--
L-10	3/6/86	7	1.0	None	0	5	2	8	--	--
				PH	500	5	2	8	--	--
				PH	1,000	5	2	6	--	--
				PH	2,000	5	2	0	--	--
				PH	4,000	5	2	3	--	--
				PH	8,000	5	2	11	--	--

[1] Items per gut.

larvae must be transferred and counted, even with careful handling, some damage is inflicted. Often there is a fairly high rate of mortality in some batches of newly hatched larvae, even without handling.

RESULTS

General Observations

Egg Development, Mortality and Hatching Rate

Nearly total egg survival was observed after 24 h in all treatments of experiment E-1 with no differences in rate of development, up to and including the highest sediment loading of 8,000 mg of sediment per liter (Table 2). The sediment used in the first experiment was carbonate material dredged from the Barbers Point Deep Draft Harbor on Oahu. In experiment E-2, eggs were examined periodically but did not show differences in development rate. In experiment E-3, egg hatch was nearly 100% in all treatments as inferred by the empty egg cases with circular escape holes. A few eggs failed to hatch, but these were not restricted to any treatment and did not seem to be related to sediment loading level. This line of investigation was terminated because we observed little or no effect of sediment on development rate, egg mortality rate, and hatching rate even with 96 h of exposure to extremely high levels of suspended solids.

Larva Mortality Rate

Three facts are important in reviewing the results of the larval fish experiments presented in Table 3. First, we occasionally observed high mortality in a control treatment with some batches of larvae. Note results of experiments L-1, L-2, L-7, and L-8. Second, egg quality and the resultant larvae condition may vary considerably among batches. We can generally compare results of treatments within an experiment, but not between experiments. Third, the sediment loading was set at very high levels in the preliminary experiments, giving us a very large margin for error when applying the resulting mortality data (i.e., no mortality observed at high levels of sediment loading) to the "real world" situation. In addition, the experimental fish larvae were stressed by handling and presumably were in poor condition compared to their wild counterparts. In this respect the data are conservative and can be applied to field situations where the larvae are probably in much better condition and more capable of withstanding sediment stress.

In many of the experimental runs (experiments L-4, L-5, L-9, L-10), we observed little or no mortality at extremely heavy loadings (1,000 mg/L or more) of red clay, manganese crust, dredged material from the Pearl Harbor Shipyard area, kaolin, and bentonite. In other runs, we observed higher mortality that seemed to be related to the condition of the animals rather than the experimental treatments (experiments L-1, L-2, L-6, L-7, L-8). In either case the presence of extremely heavy loading of suspended solids had little apparent effect on the pattern of mortality.

An anomalous situation occurred in experimental treatments containing bentonite. This clay is atypical in that it swells when wet and can form flocs when put into suspension. The flocs appeared to trap larvae and caused higher mortality (experiments L-3 and L-8). For reasons that we cannot explain, bentonite did not cause excessive mortality in experiment L-5. Perhaps the larvae were originally in better condition. In any event this area needs more investigation. Any type of ocean mining or ocean dumping operation that precipitates flocs will be a cause of greater concern.

Larval Feeding Rate

Gut content analysis indicates that high concentrations of suspended solids severely impacted the ability of larvae to feed in the 2-h exposure (Table 3, experiment L-6) and the 24-h exposure (Table 3, experiment L-7). Even a 2-h reduction in feeding could be a serious problem for larvae in poor nutritional condition. We suspect that was the situation in experiment L-6 at the 8,000 mg/L treatment level where 100% mortality resulted from a 2-h exposure.

Larval Behavior in Relation to Sediment Plumes

During the course of the above experiments, it became apparent that the fish larvae were capable of rising above a turbidity plume. Larvae would rise to the surface as sediment slurry was slowly being added to the containers. Larvae caught by the plume moved vertically into water above the turbid layer. Aeration produced a gentle current in the containers that kept the larvae mixed throughout the water column, but they would move to the surface as soon as aeration was terminated.

DISCUSSION

The results of these experiments with eggs and larvae of the dolphin are consistent with results of a large body of literature on effects of suspended solids on other pelagic biota. Based on our observations, it appears that eggs and larvae of dolphin are not extremely sensitive to the increased loading of sediment that might result from marine mining, ocean dumping or coastal construction. As stated earlier, such activities might produce loading levels of from 5 to 50 mg/L of suspended solids at the point of discharge, but sediment concentration decreases rapidly as the plume disperses. High concentrations are extremely localized (to within a few hundreds of meters from the discharge point) and do not persist very long (perhaps for 15 min) before mixing diminishes concentration to a few milligrams per liter. The increased density of water containing the solids leads to rapid sinking. Waves and currents rapidly disperse the remaining solids. A realistic loading level for a large plume is on the order of 1 mg/L. Eggs of this species were cultured at extremely high levels of suspended solids (up to 8,000 mg/L) throughout the entire development time without any apparent increase in mortality or lowering of hatching success. Similar results on other species have been reported (Boehlert et al. 1983). Likewise, larvae were relatively insensitive to extremely heavy loadings exceeding 500 to 1,000 mg/L for various sediments of the type that most commonly impact the pelagic realm due to human activity.

Suspended solid concentration did not influence mortality in most situations, but did have a dramatic impact on feeding rate as previously shown by Boehlert and Morgan (1985). However, available field data suggest that real world turbidity plumes will not be dense enough or persistent enough to severely impact larval feeding rate.

Larvae have a very limited swimming ability and would seem to be unable to avoid sediment plumes. We noted that although swimming speed is not great in larval fishes, their vertical rate of movement can allow them to escape plumes in stratified water masses. The vertical distance required to escape a surface plume is only a matter of a few meters, whereas horizontal extent of a plume is much greater.

In conclusion, we found that it was very difficult to kill eggs or larvae of mahimahi, even with extremely heavy loadings of various types of sediment that might result from ocean dumping, ocean mining, or coastal construction activities. This observation is in agreement with the conclusions of other workers such as Hirota (1981), who conducted experiments with zooplankton, and Matsumoto (1984), who summarized existing data on fishes and fish larvae. Other environmental factors such as temperature and nutrition seem to be extremely important. Effects of human activity on modification of these parameters might have a far greater impact on fish stocks than the direct effect of high levels of sediments.

ACKNOWLEDGMENTS

Samples of pelagic red clay, carbonate ooze, and manganese crust were provided by E. DeCarlo and dredgings from Pearl Harbor, Oahu were provided by D. Somerton. Size grain analysis of suspended material used in the experiments was done by J. Finn.

REFERENCES

Barry, M.
1978. Behavioral response of the yellowfin tuna, Thunnus albacares, and kawakawa, Euthynnus affinis, to turbidity. U.S. Dep. Commer., Natl. Tech. Inf. Serv., Springfield, Va., NTIS Rep. No. PB/297106/AS, 31 p. + 21 tables.

Boehlert, G. W., P. L. Jokiel, and D. J. Mackett.
1985. Issues in fisheries habitat conservation and research for the Hawaiian Archipelago and central Pacific. Results of a planning workshop 27-28 June 1985. Natl. Mar. Fish. Serv., NOAA, Honolulu, Hawaii. Southwest Fish. Cent. Admin. Rep. H-85-10, 39 p.

Boehlert, G. W., and J. B. Morgan.
1985. Turbidity enhances feeding abilities of larval Pacific herring, Clupea harengus pallasi. Hydrobiologia 123:161-170.

Boehlert, G. W., J. B. Morgan, and M. M. Yoklavich.
1983. Effects of volcanic ash and estuarine sediment on the early life history stages of the Pacific herring, Clupea harengus pallasi. Water Resour. Inst. Tech. Rep. WRRI-87, Oregon State Univ., Corvalis, Oregon, 72 p.

Chan, A. T., and G. C. Anderson.
1981. Environmental investigation of the effects of deep-sea mining on marine phytoplankton and primary productivity in the tropical eastern North Pacific Ocean. Mar. Min. 3:121-149.

Chapman, G. A.
1979. Honolulu International Airport reef runway post-construction environmental impact report. Vol. 2. Technical report to the Department of Transportation, Air Transportation Facilities Division, State of Hawaii by Parsons, Hawaii, 137 p.

Chave, K. E., and J. N. Miller.
1977. Baseline studies and evaluation of the physical, chemical, and biological characteristics of nearshore dredge spoil disposal, Pearl Harbor, Hawaii. Final report. Prepared for Pacific Division Naval Facilities Engineering Command, Honolulu, Hawaii. Environmental Center, University of Hawaii, 184 p.

Environmental Protection Agency.
1980. Environmental impact statement (EIS) for Hawaii dredged material disposal sites designation. Prepared by the U.S. Environmental Protection Agency, Oil and Special Materials Control Division, Marine Protection Branch, Washington, D.C. 20460, 276 p.

Harrison, J. T.
1986. The 40 MWe OTEC plant at Kahe Point, Oahu, Hawaii. A case study of potential biological impacts. Natl. Mar. Fish. Serv., NOAA, Honolulu, Hawaii. Southwest Fish. Cent. Admin. Rep. (In prep.)

Hirota, J.
1981. Potential effects of deep-sea minerals mining on macrozooplankton in the North Equatorial Pacific. Mar. Min. 3:19-57.

Lavelle, J. W., and E. Ozturgut.
1981. Dispersion of deep-sea mining particulates and their effect on light in ocean surface layers. Mar. Min. 3:185-212.

Lavelle, J. W., E. Ozturgut, E. T. Baker, and S. A. Swift.
1982. Discharge and surface plume measurements during manganese nodule mining tests in the North Equatorial Pacific. Mar. Environ. Res. 7:51-70.

Matsumoto, W. M.
1984. Potential impact of deep seabed mining on the larvae of tunas and billfishes. U.S. Dep. Commer., NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-44, 53 p.

National Oceanic and Atmospheric Administration.
1981. Deep seabed mining. Final Programmatic Environmental Impact Statement. U.S. Dep. Commer., NOAA, Office Ocean Minerals and Energy, Wash. D.C., Vol. 1, 295 p.

Ozturgut, E., J. W. Lavelle, O. Steffin, and S. A. Swift.
1980. Environmental investigation during manganese nodule mining tests in the North Pacific in November 1978. U.S. Dep. Commer., NOAA Tech. Memo., ERL MESA-48, 50 p.